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NASA'S BIOMASS PRODUCTION CHAMBER: A TESTBED FOR BIOREGENERATIVE LIFE SUPPORT STUDIES

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ABSTRACT

The Biomass Production Chamber (BPC) located at Kennedy Space Center, FL, USA provides a large (20 m^2 area, 113 m^3 vol.), closed environment for crop growth tests for NASA's Controlled Ecological Life Support System (CELSS) program. Since the summer of 1988, the chamber has operated on a near-continuous basis (over 1200 days) without any major failures (excluding temporary power losses). During this time, five crops of wheat (64-86 days each), three crops of soybean (90 to 97 days), five crops of lettuce (28-30 days), and four crops of potato (90 to 105 days) were grown, producing 481 kg of dry plant biomass, 196 kg edible biomass, 540 kg of oxygen, 94,700 kg of condensed water, and fixing 739 kg of carbon dioxide. Results indicate that total biomass yields were close to expected values for the given light input, but edible biomass yields and harvest indices were slightly lower than expected. Stand photosynthesis, respiration, transpiration, and nutrient uptake rates were monitored throughout growth and development of the different crops, along with the build-up of ethylene and other volatile organic compounds in the atmosphere. Data were also gathered on system hardware maintenance and repair, as well as person-hours required for chamber operation. Future tests will include long-term crop production studies, tests in which nutrients from waste treatment systems will be used to grow new crops, and multi-species tests.

INTRODUCTION

The summer of 1994 marks the sixth year of near-continuous operation of NASA's CELSS Biomass Production Chamber (BPC) at Kennedy Space Center, FL, USA. The BPC has been the centerpiece for the CELSS Breadboard Project for studying plant growth and waste recycling in a closed system at a one-person scale. The BPC provides 20 m^2 of plant growing area and a closed volume of 113 m^3 (including air ducting). Lighting is provided by 96 400-W high-pressure sodium lamps, and temperature control is provided by two 52-kW (15-ton) chilling units, three 50-kW heating elements, and two 30-kW air circulation fans. Since its initial construction, the chamber has undergone continual changes and upgrades to the hardware and control systems. These have included addition of high resolution (0.01 %) oxygen monitoring (fall 1989), tests with metal halide lamps (spring 1990), addition of nutrient solution cooling coils (spring 1991), separation of the upper and lower halves of the chamber (spring 1992), conversion to UNIX-based computer monitoring system (summer 1992), addition of a condensate recycling system (summer 1992), addition of fan speed controllers (fall 1992), addition of oxygen separators (fall 1992), addition of an atmospheric pressure control system (summer, 1993), and conversion to a UNIX-based computer control system (spring 1994). Throughout this time, the BPC has served as a test platform for several experimental sensors developed from U.S. government small business innovative research (SBIR) grants. Further details on the history and development of the chamber can be found in references /1-5/.

The early emphasis for Breadboard Project testing focused on plant production studies with the BPC. These studies were designed using inputs from university-based investigations of different plant species--wheat, soybean, lettuce, and potato /6-9/. The report that follows is a compilation of results from these plant tests since 1988.

METHODS AND MATERIALS

All plants were started from seed or plantlets (potato) and grown inside the chamber for their entire production cycle using a recirculating nutrient film (hydroponic) technique (NFT) /10/. A modified 1/2 strength Hoagland nutrient solution with nitrate as the sole source of nitrogen was used for all studies. Solution pH was automatically controlled between 5.6 and 6.0 with additions of 0.4 M nitric acid, and electrical conductivity was maintained at 0.12 S m^{-1} with automatic additions of a concentrated stock solution. Water used by the plants was replenished manually on a daily basis for early studies and on an automated, real-time basis for studies after 1992. Carbon dioxide concentrations were maintained at 1000 or 1200 ppm (0.10 or 0.12 kPa) during the light cycles, and relative humidities were maintained between 70% and 80%.

Wheat (*Triticum aestivum* L.) cv. Yecora Rojo seeds were sown at a rate of 1600 per m^2 and germinated with nylon wicks in tray inserts as described by Prince and Knott /2/. Seedlings were covered with tray covers for the first 4 d after planting to maintain high humidity and aid establishment. Light was provided from high-pressure sodium (HPS) lamps either continuously or as a 20-h light / 4-h dark photoperiod (Table 1). Average canopy-level photosynthetic photon flux (PPF) for the different studies ranged from 509 to 930 µmol m^{-2} s^{-1}, depending on the amount of dimming used and the height of the plants. Temperature was maintained at 23°C throughout growth for the continuous light study and at 24°C light / 20°C dark or constant 23°C for the first 10 to 32 d followed by 20°C light / 16°C dark for the studies using a 20-h photoperiod. Plants were harvested at physiological maturity (77 to 86 d) and all plant materials were oven dried for biomass determination.

Soybean (*Glycine max* (L.) Merr.) cv. McCall seeds were germinated in a manner similar to wheat and thinned to either four or six plants per tray (12.8 or 19.2 plants per m^2) at about 10 d after planting. Lighting was provided from HPS or metal halide (MH) lamps as a 12-h light / 12-h dark or 10-h light / 14-h dark photoperiod. Average PPF levels ranged from 477 to 815 µmol m^{-2} s^{-1} depending on whether MH or HPS lamps were used. Temperatures were cycled to provide 26°C light / 20°C dark. Plants were harvested at 90 or 97 d and all materials oven dried for biomass determination.

Lettuce (*Lactuca sativa* L.) cv. Waldmann's Green seeds were germinated similar to wheat and soybean and thinned to six plants per tray (19.2 plants m^{-2}) at about 10 d after planting. Lighting was provided from either HPS or MH lamps for a 16-h light / 8-h dark photoperiod. PPF levels were dimmed to near 300 µmol m^{-2} s^{-1} for all studies, and temperatures were maintained at 23°C continuously. Plants were harvested at 28 or 30 d and head (shoot) fresh masses determined. All roots and one head from each tray were dried for biomass determinations.

Potato (*Solanum tuberosum* L.) cv. Norland and cv. Denali (first study only) were started from in vitro-propagated plantlets and thinned to two plants per tray (6.4 plants m^{-2}) at about 10 d after planting. Lighting was provided by HPS or HPS plus MH lamps as a 12-h light / 12-h dark photoperiod. For the third study, photoperiods were extended to 16, 20, or 24 h for several days during mature growth. For the fourth study, the photoperiod was extended to 16 h from day 65 until the end of the study (105 d). Average PPF levels ranged from 655 to 917 µmol m^{-2} s^{-1}. Temperature regimes varied slightly between studies but started with 24°C light / 20°C dark or 20°C light / 16°C dark and then switched to continuous 16°C for the final stages of growth to promote tuberization. Plants were harvested at 90 or 105 d and tuber fresh masses determined. All roots and shoot materials were oven dried and 100-g samples from tubers from each tray were dried for biomass determinations.

Gas exchange rates for the different crops were monitored using nocturnal and "morning" changes in CO_2 concentration (i.e., a closed system approach), or the rate of CO_2 addition during the light period to maintain a set concentration (semi-closed approach) /11,12/. Water use (evapotranspiration) by the crop stands was monitored by the amount of water condensed by the cooling coils in the air handling system each day. These values closely matched the water added to the nutrient solution systems each day. Oxygen (O_2) exchange rates were monitored using closed system calculations for studies after 1990, but the resolution of concentration changes was much lower than for CO_2. Total CO_2 fixed was calculated on the basis of dry biomass measures and carbon analyses of the tissue for the different species (viz., 40% C for lettuce, 41% C for potato, 42% C for wheat, and 46% C for soybean). Oxygen produced was estimated from the amount of CO_2 fixed assuming a 1:1 molar ratio. (Note: This assumption likely caused a slight error in oxygen production estimates for soybean, which produces more lipid and less carbohydrate than the other species).

RESULTS AND DISCUSSION

Daily integrals of PPF (photosynthetic photon flux) and yield data from the different crop tests in the BPC are shown in Table 1 and Fig. 1. Yield data for both the total biomass and the edible biomass are expressed in three ways: 1) final dry matter per unit area; 2) a rate of production or productivity (also called crop growth rate), incorporating both area and time requirements; and 3) a radiation conversion efficiency, expressing dry matter yield per mole incident photosynthetically active radiation. All data are expressed on a basis of 20 m^2 available growing area, although much of this area was not covered with leaves early in growth. Thus the data represent the operational measure of plant performance in the BPC and not necessarily the optimum for space utilization and irradiant energy conversion. This makes the results somewhat conservative, yet provides a starting point for life support system economic trade studies.

Wheat. Total biomass production from wheat was good for the given irradiance, but seed set and harvest index were only fair (30 to 35% harvest index instead of 40 to 45%)/6/. Total biomass yields were highest in the most recent test (study 931), 3.21 kg m^{-2}, where a 20-h photoperiod was used, whereas seed yields were highest from study 881, 0.92 kg m^{-2}, when continuous light was used (Table 1). Total biomass yields averaged 2.41 kg m^{-2} for all the wheat studies, while seed yields averaged 0.76 kg m^{-2}. The best rates of production were 36.9 g m^{-2} d^{-1} for total biomass (study 931) and 12.6 g m^{-2} d^{-1} for edible biomass (study 881). For all wheat studies, total biomass averaged 30.4 g m^{-2} d^{-1} and edible biomass averaged 9.7 g m^{-2} d^{-1}. Yield differences between studies could be explained largely by differences in daily PPF (Fig. 1). Radiation conversion efficiencies averaged 0.57 g total biomass per mole photons and 0.18 g of seed per mole photons.

In nearly all of our studies with Yecora Rojo wheat, leaves would eventually show chlorotic or rusty flecks and the tips of flag leaves would become necrotic. In addition, flag leaves typically showed a longitudinal, epinastic rolling of leaves. Similar controlled-environment studies in open chambers have noted flecking and tip necrosis but not any leaf rolling (B. Bugbee, per. com.), while studies in closed chambers at NASA's Johnson Space Center have noted both the flecking and the leaf rolling (D. Barta, per. com.). Thus the leaf rolling may be peculiar to closed systems. The most recent study with wheat in the BPC showed that using activated-charcoal and potassium permanganate filters in the air handling system decreased leaf rolling, suggesting that the rolling was caused by a volatile compound. In addition, plants in the air-filtered chamber became taller than those in the unfiltered, suggesting that the removal of ethylene from the air may have promoted taller growth /13/.

High humidity was critical for rapid establishment of wheat seedlings in the wick germination approach, and daily misting of the seedlings with water seemed to help. Planting, final harvesting, and threshing of seeds from heads were probably the most labor-intensive activities associated with any of the four species. In addition, the threshing and seed sifting created a great deal of air-borne chaff and dust. Because of these requirements, mechanization of planting and harvesting and dust containment systems should be a high priority for future studies with wheat.

Soybean. Total biomass and seed production from soybean in the first study (891), which had the most irradiance, was the greatest of any soybean test: 1.33 kg m^{-2} and 0.43 kg m^{-2} (Table 1). Shoots grew rapidly during this test and reached the lamp barrier at about 35 d (roughly 65 cm above the tray covers).

TABLE 1. Yields from crop tests in NASA's Controlled Ecological Life Support System (CELSS) Biomass Production Chamber.

Crop / Date	Photoper. [2] / PPF	Daily PPF	Total Biomass			Edible Biomass		
	(h) / (μmol m^{-2} s^{-1})	(mol m^{-2} d^{-1})	(kg m^{-2})	(g m^{-2} d^{-1})	(g mol^{-1} photon)	(kg m^{-2})	(g m^{-2} d^{-1})	(g mol^{-1} photon)
Wheat 881	24 / 666	57.5	2.31	31.6	0.55	0.92	12.6	0.22
Wheat 891	20 / 535	38.5	1.89	23.1	0.60	0.55	6.7	0.17
Wheat 892	20 / 691	49.7	2.21	27.3	0.55	0.66	8.1	0.16
Wheat 931	20 / 930	67.0	3.21	39.6	0.59	0.91	11.3	0.17
Soybean 891	12 / 815	35.2	1.33	15.5	0.44	0.43	5.0	0.14
Soybean 901	12 / 477	20.6	0.95	10.2	0.50	0.32	3.4	0.17
Soybean 902	10 / 644	23.2	1.04	11.2	0.48	0.39	4.2	0.18
Lettuce 902	16 / 280	16.1	0.14	5.8	0.36	0.13	5.4	0.34
Lettuce 911	16 / 293	16.9	0.18	7.5	0.44	0.16	6.7	0.40
Lettuce 921	16 / 336	19.4	0.18	7.5	0.39	0.17	7.1	0.37
Lettuce 931	16 / 291	16.8	0.20	7.7	0.46	0.19	7.1	0.42
Potato 911	12 / 655	28.3	2.28	22.4	0.79	0.74	7.3	0.26
Potato 912	12 / 866	37.4	2.53	29.1	0.78	1.10	12.6	0.34
Potato 921[3]	12 / 917	42.2	2.77	27.2	0.64	1.88	18.4	0.44
Potato 931[3]	12-16/849	42.7	2.74	27.4	0.64	1.71	16.7	0.40

[1] Data based on an available growing area of 20 m^2.
[2] Wheat, soybean, and lettuce seedlings covered for first 4 d with germination covers; potato plants covered for first 3 d; PPF = photosynthetic photon flux.
[3] Photoperiod extension tests conducted throughout growth of potato crop 921; photoperiod switched from 12 to 16 h at 65 d for potato crop 931.

Switching to MH lamps (study 901) to broaden the spectral distribution and hopefully keep stems shorter /14/ resulted in reduced yields, primarily because of the reduced PPF, but radiation conversion efficiency increased slightly. Using both MH and HPS lamps (study 902) but with a shorter photoperiod increased the partitioning to seed (i.e., harvest index), with final seed yields being nearly as high as that from a 12-h photoperiod and higher irradiance (Table 1). Because of the shorter photoperiods and lower daily PPF, average rates of production were less than half that for wheat: 12.3 and 4.2 g m^{-2} d^{-1} for total and edible biomass. The best rates of production for soybean equaled 15.5 and 5.0 g m^{-2} d^{-1} for total and edible biomass. Radiation conversion efficiencies for total biomass were only 20% less than for wheat, whereas conversion efficiencies for edible biomass were only 10% less.

As with wheat, harvest index of soybean was relatively low (30%). McCall soybean plants tested in growth- chamber studies had higher harvest indices--40 to 45% /15/, but broad-spectrum fluorescent lamps were used for these tests, and plants were exposed to some side lighting. Replacing the HPS lamps in the BPC with broad-spectrum MH lamps for the second test did not significantly increase the harvest index. However, reducing the photoperiod in the third test from 12 to 10 h increased harvest index. This was somewhat surprising because McCall is nearly day-neutral with regard to flowering and suggests that a determinate, short-day cultivar may have been better suited for the BPC, where strong control of height and flowering would be desireable.

Stem supports were needed for both soybean and wheat, otherwise stems would lodge (i.e., collapse) causing temporary gaps in the canopy and losses in photosynthetic carbon fixation. Lodging occurred in the first soybean study (891) and resulted in abscission of heavily shaded leaves and pods and leggy growth of shaded stems. Canopy support was provided in the second and third studies by allowing stems to grow through a wire fencing grid supported about 30 cm above the tray cover. As with wheat, harvesting soybean pods was labor intensive and dusty. In addition, trichomes (hairs) from the pods could be irritating to the skin after working with them for long periods. A glabrous cultivar would seem better suited for a CELSS, where threshing and processing would occur in a closed environment.

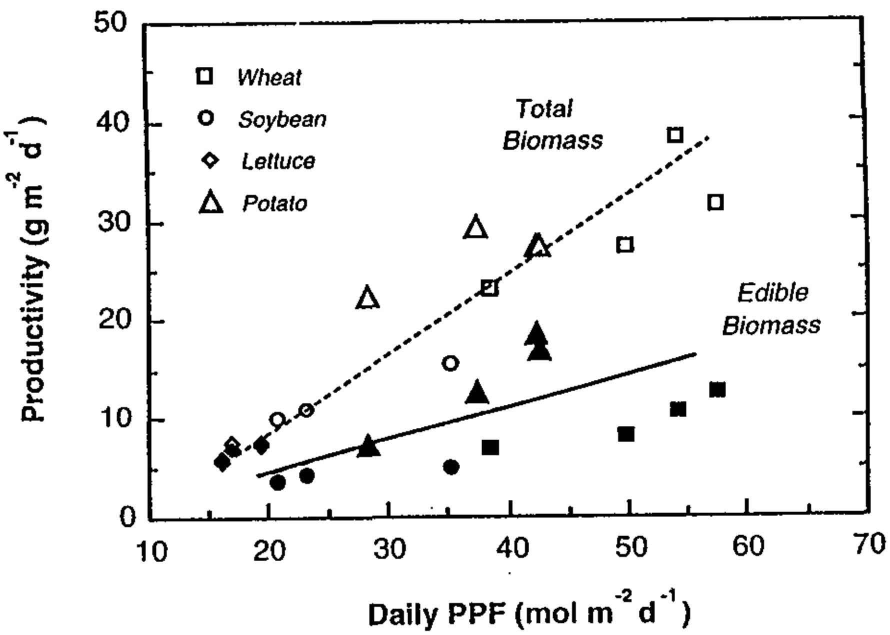

Fig. 1. Productivity of CELSS crops in NASA's Biomass Production Chamber (BPC) as a function of daily photosynthetic photon flux (PPF).

Lettuce. With the exception of the first study, lettuce yields were good and exceeded yields predicted from models developed for commerical-based lettuce production (M. Bates, per. com.) /16/. In comparison with other crops grown at higher PPF, absolute yields were low, averaging 0.18 g total biomass and 0.16 g edible biomass per m^2 (Table 1). However, radiation conversion efficiencies for edible biomass were the highest for any crop tested, averaging 0.38 g mol^{-1}. This is due in part to the high harvest index of lettuce and perhaps to higher photosynthetic efficiencies at lower irradiance. As with absolute yield, rates of biomass production were low compared with other crops because of the low PPF. In addition, the fixed spacing used for cropping cycles exaggerated time-area requirements because the canopy was open for much of the growth cycle. Full canopy cover for lettuce crops was only achieved several days before harvest, ca. 25 d after planting (DAP); thus, only about 10% of crop cycle had complete canopy cover. Wheat canopies were full from about 22 to 85 DAP (74% of crop cycle), soybean canopies were full from 28 to 97 DAP (71% of crop), and potatoes canopies were full from 35 to 105 DAP (67% of crop cycle). A simple approach to reduce wasted space and increase productivities (g m^{-2} d^{-1}) for lettuce would be to grow seedlings in a nursery at a dense spacing and then transplant them to a final spacing just prior to rapid shoot expansion.

Problems with germination and seedling establishment were encountered during the first lettuce study, where a single piece of wicking was used in each plant support slot. A double wicking germination system with dry seeds sown between pieces of nylon wicking was used for subsequent studies, and this alleviated the problem. Ancillary comparisons conducted during two BPC tests showed that seeds sown on rockwool blocks established faster than with nylon wicks, and solid media starter blocks might be explored further, particularly if they can be made from recycled materials (J.C. Sager, unpublished). As with wheat and soybean, the ability to maintain high humidity (≥85%) during seedling growth was critical for seedling establishment. Harvesting of lettuce went quickly and was the easiest of any of the four species tested. However, unlike the other crops which had storable produce, lettuce heads were perishable and had to be maintained in cold storage.

Potato. Edible biomass (tuber) yields from potatoes grown in the BPC were variable: The first test produced low yields, but the third test produced the highest edible yields of any crop tested, 1.88 kg m^{-2} (Table 1). When normalized for the cropping cycle, potatoes (study 921) also had the highest edible production rate of any species, 18.4 g m^{-2} d^{-1} (dry mass). Rates of production for all potato studies averaged 26.5 and 13.8 g m^{-2} d^{-1} for total and edible biomass. Radiation conversion efficiency for potatoes was the highest of the four species for total biomass, averaging 0.71 g mol^{-1}, and second to lettuce for edible biomass, averaging 0.36 g mol^{-1}. For all studies, total biomass production by potatoes was high, and photosynthetic rates were the highest of any species tested. When low yields occurred, problems centered on poor partitioning to tubers and low harvest index. Time of tuber initiation was roughly similar for all studies (ca. 30 to 35 d), but rapid bulking was not sustained in the first study during the middle phases of growth (40 to 80 d) and yields were low. As with soybeans, potato shoots needed support and reached the lamp barriers, which resulted in poor air circulation in the upper canopy and caused leaf temperatures to rise. Leaves near the barrier were much smaller than leaves produced early in growth, which is indicative of a high temperature, high light response /17/.

Nutrient-solution temperatures in the first potato study (911) were often > 20°C, and this likely inhibited good tuber development /17/. Additional solution cooling capabilities were added for later studies and this increased tuber yields. Potatoes grown under similar environments in growth chambers with lower irradiance tuberized reliably in NFT /18/, suggesting that some fundamental questions remain regarding consistent tuberization in the BPC environment. A clear advantage of using NFT for potato was the greatly simplified harvesting; after shoots were cleared from tray covers, tubers could be picked rapidly from the stolons and removed for weighing. However, tubers occasionally showed callus at the lenticels, particularly when they were partially submerged in the flowing nutrient solution.

Production totals for the BPC. A summary of days of operation, total biomass and edible biomass produced, CO_2 fixed, O_2 produced, and water collected from evapotranspiration from the different plant experiment in the BPC is shown in Table 2. CO_2 fixed was estimated from from the percentage of carbon in the total biomass, and O_2 was assumed to be produced on a 1:1 molar basis with CO_2 fixed.

Observations on Growth and Yield

Except for lettuce, the most obvious limiting factor to higher yields was relatively low harvest index. Total biomass production was generally good, but partitioning to seed or edible vegetative structures was inconsistent. These same species and cultivars produced higher harvest indices in growth chamber studies, suggesting that there were some environmental and/or cultural differences between the BPC and growth-chamber approaches. One obvious difference between the two environments is the closed atmosphere of the BPC and the resultant build-up of organic volatiles during growth /19/. Simultaneous comparisons of charcoal/permanganate-filtered air in one half of the BPC with unfiltered air in the other half showed that reducing these volatiles reduced leaf rolling and increased shoot heights for wheat, but had no significant effect on total yield. Clearly, further studies are needed to assess the impact of volatile compound build-up on plant growth and the BPC provides a powerful tool for such studies. Another difference was that growth chamber plants received greater side lighting. This may have reduced shoot growth and increased harvest index in the growth chambers, as well as inflate yields per unit area from growth-chamber studies /20/. We have since adopted the approach of containing growth chamber plants with a border of window screen (B. Bugbee, personal communication) to reduce edge effects and give a better predictor of plant growth in the BPC, where the plants develop a continuous canopy.

Manipulation of nutrient levels, especially nitrogen, throughout growth might be considered for controlling vegetative growth and improving harvest index. Typically, potassium and nitrate concentrations in the shoot tissues from BPC plants were high /21/, which may have kept plants vegetative.

TABLE 2. Results from crop tests conducted in NASA's Controlled Ecological Life Support System (CELSS) Biomass Production Chamber.

Crop / Date	Days of Operation	Total Biomass	Edible Biomass	CO_2[1] Fixed	O_2[1] Produced	Water Collected
	(d)	(kg)	(kg)	(kg)	(kg)	(kg)
Wheat 881[2]	77	23.06	9.24	35.5	25.8	3615
Wheat 882[3]	64	26.14	*early harvest*	40.3	29.3	5700 *(est.)*
Wheat 891	86	37.76	11.01	58.2	42.3	6903
Wheat 892	85	44.24	13.12	68.1	50.7	7809
Wheat 931	85	64.11	18.25	98.7	71.8	7500 *(est.)*
Soybean 891	90	26.62	8.58	45.0	32.7	7758
Soybean 901	97	18.94	6.34	32.0	23.3	8211
Soybean 902	97	20.80	7.79	32.5	25.6	8450
Lettuce 901	28	----	*sequential*	*harvest*	*study*	----
Lettuce 902	28	2.84	2.60	4.2	3.1	976
Lettuce 911	28	3.54	3.24	5.2	3.8	998
Lettuce 921	28	3.57	3.36	5.2	3.8	1000 *(est.)*
Lettuce 931	30	3.99	3.71	5.9	4.3	1074
Potato 911	105	45.58	14.89	68.4	49.7	8778
Potato 912	90	50.67	22.03	76.2	55.4	9361
Potato 921	105	55.42	37.64	83.1	60.5	7954
Potato 931	105	55.88	34.12	83.8	61.0	8546
Total	1229	481	196	739	540	94700

[1] Estimate from total biomass and the percentage of carbon in tissue.
[2] Only the upper half of the chamber used.
[3] 3/4 of available growing area used; plant harvest prior to maturity.

We chose to control the nutrient solutions to a constant pH and electrical conductivity for system simplicity. This seemed appropriate for gradually evolving into continuous plant-harvest operations, where one solution might be used for plants spanning a range of ages. Yet this might not be optimal for managing large batch cultures and maximizing harvest index, where for example, N levels could be reduced during crop maturation.

Problems encountered with shoots reaching the lamp barriers indicate the need to emphasize dwarf or low-growing cultivars for testing in confined systems. Regardless of the chamber and specific approach, it would seem that low-growing plants would always be advantageous for a CELSS. Increased vertical space requirements translate into increased volume requirements and chamber mass, and ultimately increased launch costs /22/.

Of the environmental factors controlled for BPC studies, light seemed to be the primary factor limiting total growth (Fig. 1). For all crops, maximum photosynthetic rates were observed soon after full canopy cover occurred, emphasizing the importance of achieving rapid canopy cover. Tests in which the PPF was varied for 1-h periods showed that photosynthetic rates of wheat, soybean, and potato stands increased linearly over the range of 0 to ~800 $\mu mol\ m^{-2}\ s^{-1}$ (Fig. 2), suggesting that the stands were below light saturation /23/. Interestingly, there was little difference in PPF responses between species after reaching complete canopy cover. Stand light compensation points were usually near 200 $\mu mol\ m^{-2}\ s^{-1}$ soon after full canopy cover, if plants were grown with maximum lighting (about 750 $\mu mol\ m^{-2}\ s^{-1}$ at tray level). Tests in which the CO_2 concentrations were allowed to drawdown to a compensation point /11,23/ showed that maximum photosynthetic rates occurred between 1200 and 1500 ppm and a sharp decline in rates when CO_2 fell below ~700 ppm, which is expected for C_3 species (Fig. 3). CO_2 compensation points for stand photosynthesis were typically between 50 and 100 ppm.

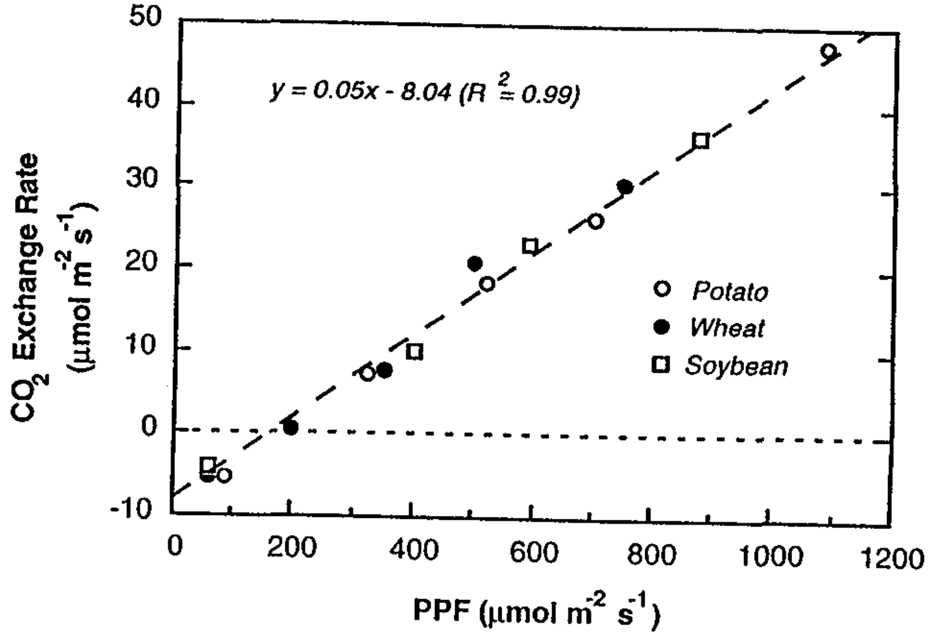

Fig. 2. Effect of photosynthetic photon flux (PPF) on photosynthetic (CO_2 exchange) rate of crop stands.

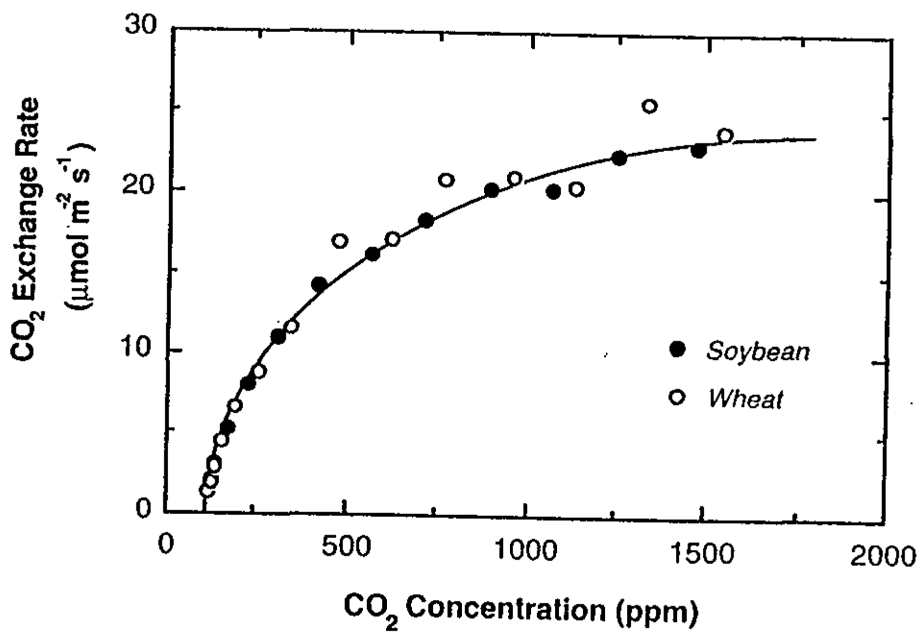

Fig. 3. Effect of CO_2 concentration on photosynthetic (CO_2 exchange) rate of wheat and soybean stands.

Short-term (1-d) temperature and humidity tests indicated that water flux through the plant stands was strongly affected by the leaf-to-air water vapor pressure deficit (Fig. 4) /12/. Diurnal water flux trends were not monitored in initial studies, but dark-period evapotranspiration rates were often higher than expected, based on porometer measurements from upper canopy leaves in growth chamber tests. This is an interesting discrepency between single leaf and canopy measurements and should be explored further.

Future plans for the BPC include continued baseline testing with additional candidate species to determine their physiological traits and characteristic organic volatiles. In addition, a series of tests has been planned to combine crop production and resource (waste) recovery subsystems to assess operational dynamics and system mass fluxes. A series of continuous (6 to 12 month) cropping tests also is planned to assess crop productivities and hardware performance. To date, no pathogen outbreaks have occurred, but hydroponic systems have been cleaned thoroughly between plantings and the old nutrient solutions discarded. Mixed cropping scenarios where blocks of different species are grown in the chamber at the same time are also under consideration to study interactions between species and how productivities might be affected if environmental set-points are compromised for several species.

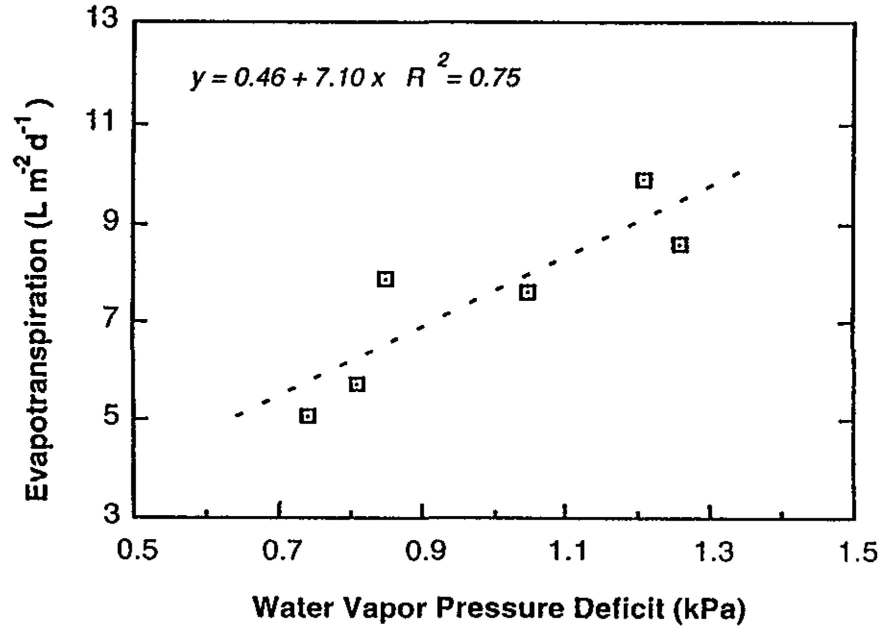

Fig. 4. Effect of water vapor pressure deficit on daily evapotranspiration (water flux) from a soybean stand.

SUMMARY

The Biomass Production Chamber (BPC) at NASA's Kennedy Space Center has been operated on a near-continuous basis for over 6 years providing baseline data for using plants in closed, life-support systems in space. Total biomass yields of the different crops (wheat, soybean, lettuce, and potato) were stongly dependent on total lighting provided to the plants and generally close to anticipated values based on university research and preliminary growth-chamber trials; however, edible yields and harvest index have sometimes fallen short of anticipated values. The findings suggest that some factors of the closed BPC environment may adversely affect partitioning to edible plant structures. All the crops could be grown satisfactorily using nutrient-film technique and high-pressure sodium lighting. Extensive data have been gathered on crop CO_2 and O_2 exchange rates, evapotranspiration, mineral nutrition, and physical systems performance and maintenance. In addition, baseline data have been gathered for volatile compounds that accumulated during crop growth. Future testing with the BPC will focus on long-term operational tests (e.g., continuous crop production) and the recycling of water, nutrients, and gases from resource recovery (waste treatment) systems. Future CELSS program testing should continue thorough cultivar screening of candidate crops prior to operational level tests, with a strong emphasis on high productivity, harvest index, and short canopy height. In addition, approaches to gather applicable stand or canopy-based yields (i.e., accounting for edge effects from side-lighting), and exploration of automation of planting, harvesting and materials handling to reduce labor requirements will be required. Systematic environmental testing of crops using response surface approaches also should be considered to define responses under suboptimal, as well as optimal conditions, and better determine the reliability of plants for life support applications.

REFERENCES

1. R.P. Prince, W.M. Knott, J.C. Sager, and S.E. Hilding, Design and performance of the KSC Biomass Production Chamber, *SAE Tech. Paper Series* 871437, Seattle, WA, USA (1987).
2. R.P. Prince and W.M. Knott, CELSS Breadboard Project at the Kennedy Space Center. In: D.W. Ming and D.L. Henninger (eds.) Lunar Base Agriculture: Soils for Plant Growth, Amer. Soc. Agron., Madison, WI, USA (1989).
3. J.C. Sager, C.R. Hargrove, R.P. Prince, and W.M. Knott, CELSS atmospheric control system. *ASAE Paper* 88-4018, Rapid City, SD, USA (1988).
4. R.E. Fortson, J.C. Sager, J.O. Bledsoe, R.M. Wheeler, and W.M. Knott, Current performance of the NASA Biomass Production Chamber, *ASAE Paper* 92-4001, Charlotte, NC, USA (1992).
5. R.M. Wheeler, C.L. Mackowiak, T.W. Dreschel, J.C. Sager, R.P. Prince, W.M. Knott, C.R. Hinkle, and R.F. Strayer, System development and early biological tests in NASA's Biomass Production Chamber. *NASA Tech. Mem.* 103494, Kennedy Space Center, FL, USA (1990).
6. B.G. Bugbee and F.B. Salisbury, Exploring the limits of crop productivity. I. Photosynthetic efficiency of wheat in high irradiance environments, *Plant Physiol.* 88, 869-878 (1988).
7. S.L. Knight and C.A. Mitchell, Effects of CO_2 and photosynthetic photon flux on yield, gas exchange and growth rate of *Lactuca sativa* L. 'Waldmanns' Green', *J. Exp. Bot.* 39, 317-328 (1988).
8. T.W. Tibbitts and R.M. Wheeler, Utilization of potatoes for bioregenerative life support systems, *Adv. Space Res.* 7, 115-122 (1987).
9. C.D. Raper Jr., K. Vessey, and L.T. Henry, Increase in nitrate uptake by soybean plants during interruption of the dark period with low intensity light, *Physiol. Plant.* 81, 183-189 (1991).
10. J.B. Jones, A guide for hydroponic and soilless culture grower, Timber Press, Portland, OR, USA (1983).
11. R.M. Wheeler, Gas exchange measurements using a large, close plant growth chamber. *HortScience* 27, 777-780 (1992).
12. K.A. Corey and R.M. Wheeler, Gas exchange in NASA's Biomass Production Chamber. A preprototype closed human life support system, *BioScience* 42, 503-509 (1992).
13. R.M. Wheeler, K.A. Corey, B.A. Vieux, S.W. Mosakowski, J.C. Sager, and W.M. Knott, Ethylene evolution by crop stands grown in a closed, controlled environment. *HortScience* 27, 682 (1992).
14. R.M. Wheeler, C.L. Mackowiak, and J.C. Sager, Soybean stem growth under high-pressure sodium with supplemental blue lighting, *Agron. J.* 83, 903-906 (1991).
15. R.M. Wheeler, C.L. Mackowiak, L.M. Siegriest, and J.C. Sager, Supraoptimal carbon dioxide effects on growth of soybean [*Glycine max* (L.) Merr.], *J. Plant Physiol.* 142, 173-178 (1993).
16. R.M. Wheeler, C.L. Mackowiak, J.C. Sager, N.C. Yorio, W.M. Knott, and W.L. Berry, Growth and gas exchange by lettuce stands in a closed environment, *J. Amer. Soc. Hort. Sci.* 119, 610-615 (1994).
17. R.M. Wheeler, K.L. Steffen, T.W. Tibbitts, and J.P. Palta, Utilization of potatoes for life suppoprt systems. II. The effects of temperature under 24-h and 12-h photoperiods, *Amer. Potato J.* 63, 639-647 (1986).
18. R.M. Wheeler, C.L Mackowiak, J.C. Sager, W.M. Knott, and C.R. Hinkle, Potato growth and yield using nutrient film technique (NFT), *Amer. Potato J.* 67, 177-187 (1990).
19. J.H. Batten, B.V. Peterson, E. Berdis, and R.M. Wheeler, Biomass production chamber air analysis of wheat study (BWT931), *NASA Tech. Mem.* 109192, Kennedy Space Center, FL, USA (1993).
20. D.W. Hand, J. Warren-Wilson, and B. Acock, Effects of light and CO_2 on net photosynthetic rates of stands of aubergine and *Amaranthus*, *Ann. Bot.* 71, 209-216 (1993)
21. R.M. Wheeler, W.L. Berry, C.L. Mackowiak, K.A. Corey, J.C. Sager, M.M. Heeb, and W.M. Knott, A data base of crop nutrient use, water use, and carbon dioxide exchange in a 20 square meter growth chamber: I. Wheat as a case study, *J. Plant Nutr.* 16, 1881-1915 (1993).
22. A. Drysdale, J. Sager, R. Wheeler, R. Fortson, and P. Chetirkin, CELSS engineering parameters, *SAE Tech. Paper Series* 932130, Colorado Springs, CO, USA (1993).
23. R.M. Wheeler, K.A. Corey, J.C. Sager, and W.M. Knott, Gas exchange characteristics of wheat stands grown in a close, controlled environment, *Crop. Sci.* 33, 161-168 (1993).